# MASTER OSCILLATOR – POWER AMPLIFIER EXCIMER LASER SYSTEM

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## CLAIM OF PRIORITY

This patent application claims priority to U.S. provisional patent applications "MASTER OSCILLATOR – POWER AMPLIFIER EXCIMER LASER SYSTEM," No. 60/424,186, filed November 5, 2002; "MOPA EXCIMER LASER SYSTEM," No. 60/426,659, filed November 15, 2002; "EXCIMER LASER WITH INTEGRATED PULSE EXTENDER," No. 60/434,695, filed December 18, 2002; and "MOPA EXCIMER LASER SYSTEM," No. 60/448,630, filed February 20, 2003, all of which are incorporated herein by reference.

## CROSS-REFERENCE TO RELATED APPLICATIONS

The following applications are cross-referenced and hereby incorporated herein by reference:

U.S. Patent Application No. 20020021729, entitled "NARROW BANDWIDTH OSCILLATOR-AMPLIFIER SYSTEM," to Klaus Vogler, filed February 21, 2002; and

US Patent No. 6,389,045 B1, entitled "OPTICAL PULSE STRETCHING AND SMOOTHING FOR ARF AND F2 LITHOGRAPHY EXCIMER LASERS," to Klaus Mann et al., filed April 17, 2000.

## TECHNICAL FIELD OF THE INVENTION

The present invention relates to systems and methods of optical decoupling useful in a Master Oscillator - Power Amplifier (MOPA) system, wherein the power amplifier can be configured as single-pass or multiple pass.

## BACKGROUND

Semiconductor manufacturers are currently using deep ultraviolet (DUV) lithography tools based on KrF-excimer laser systems, operating at wavelengths around 248 nm, as well

as ArF-excimer laser systems, which operate at around 193 nm. Vacuum UV (VUV) tools are based on $F_2$-laser systems operating at around 157 nm. These relatively short wavelengths are advantageous for photolithography applications because the critical dimension, which represents the smallest resolvable feature size that can be produced photolithographically, is proportional to the wavelength used to produce that feature. The use of smaller wavelengths can provide for the manufacture of smaller and faster microprocessors, as well as larger capacity DRAMs, in a smaller package. In addition to having smaller wavelengths, such lasers have a relatively high photon energy (i.e., 7.9 eV) which is readily absorbed by high band gap materials such as quartz, synthetic quartz ($SiO_2$), Teflon (PTFE), and silicone, among others. This absorption leads to excimer and molecular fluorine lasers having even greater potential in a wide variety of materials processing applications. Excimer and molecular fluorine lasers having higher energy, stability, and efficiency are being developed as lithographic exposure tools for producing very small structures as chip manufacturing proceeds into the 0.18 micron regime and beyond. The desire for such submicron features comes with a price, however, as there is a need for improved processing equipment capable of consistently and reliably generating such features. Further, as excimer laser systems are the next generation to be used for micro-lithography applications, the demand of semiconductor manufacturers for powers of 40 W or more to support throughput requirements leads to further complexity and expense.

## BRIEF DESCRIPTION OF THE DRAWINGS

**Figure 1** is a diagram of a MOPA configuration that can be used in accordance with one embodiment of the present invention.

**Figure 2** is a plot showing (a) the intensity of a beam over subsequent passes through a PA, and (b) the allowable jitter over time in accordance with one embodiment.

**Figure 3** is a diagram of another MOPA configuration that can be used in accordance with one embodiment of the present invention.

**Figure 4** is a diagram of another MOPA configuration that can be used in accordance with one embodiment of the present invention.

**Figure 5** is a diagram of another MOPA configuration that can be used in accordance with one embodiment of the present invention.

**Figure 6** is a diagram of another MOPA configuration that can be used in accordance with one embodiment of the present invention.

**Figure 7** is a diagram of a PA beam path that can be used in accordance with embodiments of the present invention.

**Figure 8** is a diagram of another PA beam path that can be used in accordance with embodiments of the present invention.

**Figure 9** is a diagram of another PA beam path that can be used in accordance with embodiments of the present invention.

**Figure 10** is a diagram of a beam matching unit that can be used with embodiments of the present invention.

**Figure 11** is a diagram of another PA beam path that can be used in accordance with embodiments of the present invention.

**Figure 12** is a diagram of a MOPA configuration having a pulse extender that can be used in accordance with one embodiment of the present invention.

**Figure 13** is a diagram showing pulses along a beam path through a MOPA configuration in accordance with one embodiment of the present invention.

## DETAILED DESCRIPTION

As semiconductor manufacturers move toward the production of chips with smaller sizes, the requirements on the processing and manufacturing equipment, including the laser light sources, are ever increasing. In laser systems used for photolithography applications, for example, it would be desirable to move toward higher repetition rates, increased energy stability and dose control, increased system uptime, narrower output emission bandwidths, improved wavelength and bandwidth accuracy, and improved compatibility with stepper/scanner imaging systems. It also would be desirable to provide lithography light sources that deliver high spectral purity and extreme power, but that also deliver a low cost chip production. Requirements of semiconductor manufacturers for higher power and tighter bandwidth can place excessive, and often competing, demands on current single-chamber-based light sources. Systems and methods in accordance with various embodiments of the present invention can overcome many of these obstacles by taking advantage of a dual-gas-discharge-chamber technology referred to herein as MOPA (Master Oscillator - Power

Amplifier) technology. MOPA technology can be used to separate the bandwidth and power generators of a laser system, as well as to control each gas discharge chamber separately, such that both the required bandwidth and pulse energy parameters can be optimized. Using a master oscillator (MO), for example, an extremely tight spectrum can be generated for high-numerical-aperture lenses at low pulse energy. A power amplifier (PA), for example, can be used to intensify the light, in order to deliver the power levels necessary for the high throughput desired by the chip manufacturers. The MOPA concept can be used with any appropriate laser, such as KrF, ArF, and $F_2$–based lasers.

In certain embodiments of the present invention, additional advantages can be obtained by using a multi-pass power amplifier configuration with the various MOPA configurations. In a "multi-pass" amplifier configuration, an oscillator beam output from an oscillator makes at least two separate passes through the discharge chamber of the amplifier. The use of at least one additional pass can allow for an increase in gain, and can provide the ability to obtain a higher output pulse energy with a lower input pulse energy. Such a configuration can also be used to drive the PA into a state of saturation, thereby reducing pulse-to-pulse energy fluctuations and improving beam homogeneity. A multi-pass configuration also can allow the system to effectively "stretch" the amplified pulse, which can lead to a relaxed requirement of the synchronization precision and, therefore, greater pulse energy reproducibility.

Running an extremely high gain in a multi-pass amplifier can have some drawbacks, however, as there can be an increased lever of amplified spontaneous emission (ASE) in the laser output. The high gain can also result in undesirable feedback to the MO. Therefore, certain embodiments provide for an optical decoupling between the PA and the MO, as well as between passes of a beam through the PA. By optically decoupling the PA and the MO, a high output pulse energy can be obtained with low energy fluctuations. Further, ASE can be suppressed to less than 0.1% of the total laser output.

**Figure 1** shows a generalized configuration **100** that can be used in accordance with one embodiment of the present invention. A master oscillator (MO) **102** is formed by a first discharge chamber **104** having disposed therein a pair of electrodes **106** on either side of the beam path through the MO. The MO further includes a line-narrowing optics module **108** for narrowing the oscillator beam in the discharge chamber **104**, and an outcoupler module **122**.

Although not shown, it should be recognized by one of ordinary skill in the art that various other elements can be included in the oscillator which are not shown, such as output beam diagnostic tools, circuits for forming a discharge pulse, and electronic controls.

A power amplifier (PA) **112** can be positioned along the beam path a distance from the MO, such as a distance comparable to the pulse length in free space, or at least half of the pulse length. Such separation can cause any ASE from the PA to be delayed with respect to the initial stages of pulse formation in the MO, such that pulse formation is not disturbed. A spatial filter **110** can be located along the beam path between the MO and the PA, which can serve to further de-couple the MO and the PA, and which can modify the size of beam size as described herein. The PA can include a discharge chamber **114** containing at least one pair of electrodes **116** on either side of the beam path. Once the beam makes a first pass through the PA, the beam can pass through a second spatial filter **118** and be retro-reflected by a retro-reflector **120** for a second pass through the second spatial filter **118** and the PA **112**. The retro-reflector **120** can be removed a distance from the PA, such as a distance that is equal to a portion of the pulse length. Such separation can help to increase the "time window" of amplification, resulting in the overall gain being less sensitive to the time jitter between successive discharges. In certain embodiments, the retro-reflector must be a distance of at least half the pulse length away from the MO. This separation ensures that photons originating in the oscillator and amplified in the PA, which pass through the spatial filters, will not be amplified in the MO, as they arrive after the inversion population has been depleted. The second spatial filter **118** serves to decouple successive passes of the beam through the PA, thereby reducing the amount of the ASE in the output beam. The spatial filters used can vary between embodiments, but generally can be any appropriate spatial filters, such as those formed by cylindrical lenses and slits. In certain embodiments, it may be less desirable to use commonly known spatial filters based on spherical lenses and pin-holes. In utilizing cylindrical lenses to form a spatial filter, a much lower intensity can be obtained at the focal point, the formation of a plasma can be avoided, and the lifetime of the slits can be greatly extended.

Spatial filters are well known in the art, and are commonly used for removing high-spatial frequency features from beams, as well as combining the functions of magnification and imaging. See, for example, J.T. Hunt, P.A. Renard, W.W. Simmons, Applied optics,

vol. 16, p. 770 (1977) or J.T. Hunt, J.A. Glaze, W.W. Simmons, P.A. Renard Applied Optics, vol. 17, p. 2053 (1978). Such spatial filters consist of two spherical lenses, similar to that shown in Figure 10, which form a focal point between the lenses. The pinhole is placed at the focal point, so that only the highly spatially coherent (low divergence) portion of the beam is transmitted. In certain embodiments, cylindrical lenses are used instead of commonly used spherical lenses, and a slit aperture is used instead of a pinhole. Since the beam is focused into a slit aperture instead of a pinhole, the intensity in the focal point can be reduced by orders of magnitude as compared to a standard pinhole-based spatial filter. Thus, wear and damage to the slit aperture can be greatly reduced.

As mentioned above, the use of a multi-pass amplifier configuration can allow the system to effectively "stretch" the amplified pulse, which can lead to greater pulse energy reproducibility. **Figure 2** illustrates one example of the effect of apparent pulse stretching in the amplifier, due to the time delay (Δt) between successive passes. **Figure 2(a)** shows the intensity of laser light as a function of time for each pass through the amplifier, as "seen" by an observer at the amplifier. The solid waveform shows intensity originating from the laser pulse on the first pass through the amplifier, while the dashed curve shows the intensity of the second pass. The delay Δt between those curves is caused by propagation delay between the passes. **Figure 2(b)** shows in the solid curve the gain in the PA as a function of time. The intensity of laser light is shown as a function of time, as "seen" by an observer at the amplifier. The solid waveform shows intensity originated from the laser pulse on the first pass through the amplifier, while the dashed curve is the intensity of the second pass. The delay Δt between those is caused by propagation delay between the passes. The bottom diagram shows in solid curve the optical gain in the amplifier as a function of time. The optimum amplification occurs when the laser pulse overlaps temporarily with the gain pulse. S since the laser pulse intensity is present in the amplifier for a duration longer than that of a single pass, the timing of the gain pulse can become less critical. In fact, the actual delay can deviate from the optimal value without dramatic effect on the output pulse energy and/or spectrum. The dashed line illustrates the position of the gain pulse with imperfect timing control. Even though timing of the gain pulse is varied over a certain range, the gain pulse still overlaps with the laser pulse.

**Figure 3** shows a configuration in accordance with another embodiment of the present invention. Reference numbers are carried over between Figures where appropriate, for sake of simplicity. In this embodiment, the oscillator beam is reduced in size when passing through a first spatial filter and set of beam shaping optics **202**. A pair of HR mirrors **204, 206** can be used to direct the beam such that the beam passes through the PA **112** in a direction substantially anti-parallel to the direction of the beam through the MO **102**. On the first pass of the beam through the PA, the beam overlaps with only a small portion of the gain medium between the electrodes **116** in the discharge chamber **114**. The energy of the pulse is insufficient to saturate the gain, such that partial overlap is not problematic. A second spatial filter and set of beam-shaping optics **208** is used to de-couple the beam between passes through the PA, as well as to expand the beam. The second spatial filter and set of beam-shaping optics **208** can be placed before or after the beam is again reflected using a pair of high reflector (HR) mirrors **210, 212**. It should be understood that the HR mirrors are only exemplary, and that any appropriate optical device and or element can be used to appropriately redirect the beam. Also, while the beam path is shown being "folded" in the plane containing the discharge electrodes, or the "long" axis of the beam, a similar arrangement can be implemented using the "short" axis of the beam. When the beam passes through the PA a second time, stored energy is removed from the remaining volume of the gain medium in the discharge chamber **114**. Further, expanding the beam can help to remove additional stored energy from the gain medium since the pulse energy will be greater on the second pass.

A power amplifier (PA) in some embodiments includes a discharge chamber filled with a laser gas, such as a gas including molecular fluorine, and a buffer gas. Electrodes are positioned in the discharge chamber that are connected to a discharge circuit, such as an electrical delay circuit, for energizing the molecular fluorine in the chamber. The discharge of the PA can be timed to be at, or near, a maximum in discharge current when a pulse from the master oscillator (MO) reaches the amplifier discharge chamber. An aperture can be positioned between the discharge chamber and the beam expander, as well as on the other side of the discharge chamber. Various line-narrowing optics can be used, which can include one or more tuned or tuneable etalons. In one embodiment, the one or more etalons are tuned for maximum transmissivity of a selected portion of the spectral distribution of the beam, and

for relatively low transmissivity of outer portions of the spectral distribution of the beam. A prism beam expander can be provided before the etalons in order to expand the beam that is incident upon the etalon(s). Two etalons can be used and tuned, as is known in the art, such that only a single interference order of the beam is selected. The line-narrowing optics can further include a grating for selecting a single interference order of the etalon(s) corresponding to the selected portion of the spectral distribution of the beam. Instead of including an etalon, the line-narrowing optics may instead include only a beam expander and a diffraction grating. A beam expander in one such embodiment includes two, three, or even four VUV transparent prisms before the grating. The grating can have a highly reflective surface serving as a resonator reflector in addition to dispersing the beam.

The line-narrowing optics can include an etalon output coupler tuned for maximum reflectivity of a selected portion of the spectral distribution of the beam, and for relatively low reflectivity of outer portions of the spectral distribution of the beam. Such a system can also include optics such as a grating, dispersive prism, or etalon, which may follow a beam expander, for selecting a single interference order of the etalon output coupler. One or more apertures can be used for reducing stray light and divergence within the resonator of the PA.

In any layout or configuration in which a grating is utilized, a highly reflective mirror can be disposed after the grating, along the path of the beam, such that the grating and HR mirror form a Littman configuration. Alternatively, the grating can serve to retro-reflect as well as disperse the beam in a Littrow configuration. A transmission grating, or grism, can also be used.

A buffer gas used in a discharge chamber can include any appropriate gas, such as for example neon or helium, for pressurizing the gas mixture in order to increase the output energy for a given input energy. Sufficiently pressurizing the gas mixture can also work to increase the energy stability, gas and tube lifetime, and pulse duration. A laser system can further include a gas supply system for transferring molecular fluorine into discharge chamber, in order to replenish the molecular fluorine. A processor or processing device can be used with the gas supply system to control the molecular fluorine concentration within the discharge chamber, in order to maintain the molecular fluorine concentration within a predetermined range of optimum performance of the laser.

A spectral filter can be positioned between the master oscillator and the power amplifier for further narrowing the line width of the output beam of the oscillator. The spectral filter can include, for example, one or more etalons following a beam expander. Alternatively, the spectral filter can include a grating for dispersing and/or narrowing the beam. Where a grating is used, the spectral filter can include a lens to focus the beam through a slit and onto a collimating optic prior to impinging upon the beam expander-grating combination.

Components of a laser system can include those discussed in published U.S. Patent Application No. 2002/0021729, incorporated herein by reference above, which discloses a molecular fluorine ($F_2$) laser system including a seed oscillator and power amplifier. The seed oscillator comprises a laser tube including multiple electrodes therein, which are connected to a discharge circuit. Seed radiation can alternatively be provided by an excimer lamp maintained at low pressure. The laser tube is part of an optical resonator for generating a laser beam including a first line of multiple characteristic emission lines around 157 nm. The laser tube can be filled with a gas mixture including molecular fluorine and a buffer gas. The gas mixture can be at a pressure below that which results in the generation of a laser emission, including the first line around 157 nm having a natural line width of less than 0.5 pm, without an additional line-narrowing optical component for narrowing the first line. The power amplifier increases the power of the beam emitted by the seed oscillator to a desired power for applications processing.

**Figure 4** shows another configuration **300** in accordance with embodiments of the present invention. In this layout **300**, the beam again passes through a spatial filter and beam-shaping optics **302** after exiting the MO **102**. The beam is then redirected approximately 90% by an HR mirror **304** to a polarizing element **306**, which redirects the beam through the PA **112**. After exiting the PA on the first pass, the beam passes through a quarter wave plate **308** that adjusts the polarization of the beam. The beam then passes through the second spatial filter and beam shaping optics **310** before, and after, being reflected by HR mirror **312**. The reflected beam then passes again through the quarter wave plate **308** and makes a second pass through the PA. Even though the beam crosses the same area between the electrodes in the PA, the differing polarizations between passes prevents the passes from interfering with one another. After exiting the PA a second time, the beam

passes through the polarizer **306** and exits the system. Due to the polarization of the beam exiting the PA, no portion of the beam will be redirected toward the MO by the polarizer **306**, preventing ASE from interfering with the MO **102**.

**Figure 5** shows a configuration **400** wherein the beam crosses through the PA **112** at a different angle for each pass, such as an angle of approximately 0.7°. After exiting the MO **102** and passing through the spatial filter and beam shaping optics **402**, a narrowed beam is directed through the PA, using HR mirrors **404** and **406**, at an angle that is substantially non-parallel to the long axis of the PA electrodes **116**. The beam is then redirected by a pair of HR mirrors **408**, **410** through a second spatial filter and beam shaping optics **412**. The beam only passes through the second spatial filter after being redirected by HR mirrors **408** and **410**, and the beam shaping optics function to widen the beam before the beam makes a second pass through the PA. The beam then makes a second pass through the PA, at another angle substantially non-parallel to the long axis of the PA electrodes before exiting the system. The differing angles and sizes of the beam between passes allows the passes to have minimum interference with one another, providing a cleaner separation of the "incoming" and "output" beams. In another embodiment, one of the passes of the beam through the PA can be made collinear to the chamber axis, or parallel to the long axis of the electrodes.

Beam Paths Not Requiring Additional De-coupling

Systems and methods in accordance with various embodiments of the present invention can do away with the need for additional optical coupling between the MO and PA in a MOPA-based excimer laser system by utilizing any of a number of special beam paths. Using a multi-pass configuration with a power amplifier (PA) can result in a higher level of ASE in the output and feedback to the master oscillator (MO). Feedback to the MO can originate from at least two sources, including ASE and a poorly decoupled, amplified main beam. The use of a special beam path can effectively reduce the amount of ASE and feedback, such that additional optical de-coupling is unnecessary.

In a relatively simple arrangement using a double-pass amplifier, a beam is retro-reflected back into the amplifier chamber after the first pass. Thus, the beam propagates towards the oscillator on the second pass. One difficulty with such an approach is that it can be difficult to "scrape off" the entire beam after the second pass and turn the beam towards

the output of the system, as the divergence angle of an excimer laser beam can be quite high. A portion of the beam outside of the main beam cross-section can become amplified and return to the oscillator. Since this portion can have a high spatial and temporal coherence, it can be difficult to block this portion using spatial or spectral filters that otherwise can be used for de-coupling of the MO from PA. The feedback to the MO can manifest itself in another way, as the outcoupling mirror **510** of the MO and retro-reflecting mirrors of the PA effectively form a resonator, which can resonate a scattered portion of the beam in the PA. A "time delay decoupling" approach can be utilized, but the substantial space required for such an approach, such as at least 5 m of the beam path, may not be practical. Approaches in accordance with various embodiments can overcome these obstacles by ensuring that the amplified beam is always propagating in a direction away from the MO, thus preventing feedback to the MO. The ASE portion of feedback is not nearly as strong as the amplified beam, and does not cause substantial disturbance to the MO.

Certain embodiments also address the difficulty in decoupling the second pass, or any subsequent passes, from the first pass in the PA. While a spatial filter can be used between passes, such as described above, a spatial filter can require a substantial length of free propagation along the beam path. Further, folding a focused beam with mirrors may not be feasible or practical due to the high intensity of the beam. The difficulty of folding the beam within the spatial filter can lead to the minimal beam path length between passes being equal to two lengths of the spatial filter, due to retro-reflection. Besides increasing the space requirement, this extra beam path length generates an additional delay between the passes, which can lead to reduced temporal overlap with the gain pulse. It is therefore an advantage of certain embodiments to utilize the portion of the beam path between passes without adding a penalty due to an unnecessary increase in path length.

**Figure 6** shows a configuration **500** for one such embodiment, with **Figure 6(a)** showing a top view and **Figure 6(b)** showing a side view of the components. The master oscillator (MO) **504** in this layout includes a discharge chamber **506** containing at least one pair of electrodes **508**, a line narrowing module **502**, and an outcoupler **510**. After a laser beam passes from the MO, the beam enters a first spatial filter **538** positioned between the MO **504** and the PA **518**. The first spatial filter **538** in this embodiment consists of two cylindrical lenses **512** and **516**, on either side of a slit **514** along the beam path. The

orientation of the lenses and slit are shown in such a way that the slit is parallel to the "short" axis of the beam. It should be recognized by one of ordinary skill in the art that the lenses and slit of the spatial filter can also be oriented in a perpendicular direction. The decision on orientation can depend upon the resulting contrast ratio of the filter, or the ratio of the transmitted coherent portion of the beam to the transmitted spontaneous emission.

After passing through the first spatial filter **504**, the beam traverses the gain volume between the electrodes **522** in the discharge chamber **520** of the power amplifier (PA) **518**. After the first pass through the PA, the beam is folded by mirrors **524**, **526**, **534**, and **536** such that the beam can make a second pass through the PA **518**. As can be seen in the side view in **Figure 6(b)**, the beam height is a portion of the height of the gain area between the electrodes **522** in the chamber **520**, such that the two passes can effectively be "stacked" between the electrodes. The beam height, which in this embodiment is less than or equal to one half of the height of the gain medium between the electrodes, can be adjusted by selecting lens **512** and lens **516** to be of unequal focal length. Thus, the beam size will be proportional to the focal length ratio of the two lenses (**516/512**). Alternatively, the second pass through the PA can be made with an expanded beam. The beam can be expanded by placing a second spatial filter **540** in the path of the beam between the first and second passes. Expansion can be made using a second spatial filter **540** by adjusting the ratio of focal length of lenses **528** and **532** on either side of slit **530**. Alternatively, larger electrode spacing can be used in the amplifier than is used in the oscillator, such that the amplifier can accommodate both beams. It should be understood to one of ordinary skill in the art that embodiments are described using a double-pass configuration for simplicity, and that additional passes can be taken through a PA where such additional passes are advantageous. In certain instances, however, a double-pass configuration proves advantageous.

Certain advantages exist to such a beam path, as there is no retro-reflector or other optical element positioned so as to return the beam directly back into the amplifier for the second pass such that the beam is directed towards the oscillator. Despite precautions to cleanly separate a returned beam from the oncoming beam, there is typically a considerable divergence and scatter in either beam, which is inherent to the excimer lasers when a retro-reflector is used as such. Thus, a substantial portion of the amplified beam ends up going back into the oscillator and disturbing pulse formation. The returned portion of the beam can

have a very high degree of collimation and spectral purity, making the beam difficult to filter out using a spatial or spectral filter. Using a beam path in accordance with embodiments of the present invention, however, allows the beam to always be propagating away from the oscillator, such that only ASE generated in the amplifier gain volume can reach the oscillator. If necessary, additional decoupling approaches can be used, such as the addition of spatial filters **538** and **540**, which are otherwise optional, or the increasing of the distance between the MO **504** and the PA **520**, such as to approximately ½ of the pulse length.

As shown in **Figure 6**, a second spatial filter **540** for de-coupling subsequent passes through the PA can be conveniently inserted between mirrors **526** and **534**. Such placement does not incur any penalty of extra beam path due to retro-reflection. In fact, the typical discharge chamber length is perfectly suitable for a conservatively-designed spatial filter. Lenses **528** and **532** comprising the second spatial filter **540** can be also inserted between mirrors **524** and **526**, or between mirrors **534** and **536**. The above discussion regarding the orientation of cylindrical axes of the lenses and the slit applies here as well.

**Figure 7** shows a portion of a layout **600** in accordance with another embodiment of the present invention. The layout **600** is similar to the layout of Figure 6 for the beam, until the beam first passes through the PA **518**. **Figure 7(a)** shows a top view of the amplifier portion of the layout, which is similar to the top view shown in Figure 6(a). In the top view, it can be seen that the beam passes through the PA **518**, then is redirected by mirrors **602** and **604** through second spatial filter **616** comprising lenses **606** and **610** and slit **608**. After passing through the second spatial filter, the beam is redirected by mirrors **612** and **614** back through the PA. As can be seen in the side view of **Figure 7(b)** for the first pass of the beam through the PA, the path of the beam is tilted relative to the long axis of the electrodes, or the main axis of the chamber. Generally, the beam width will be somewhat smaller than the gap between the electrodes **522** in order to avoid any clipping of the beam while passing through the PA. After being redirected by the mirrors **602** and **604**, the beam passes the second spatial filter **616**, as seen in **Figure 7(c)**, at which time the width of the beam can be increased to match the size of the electrode gap. The beam width can be increased in one embodiment by appropriately selecting the ratio of the focal lengths of lenses **606** and **610** (e.g., **610/608**). Finally, the beam can be redirected by mirrors **612** and **614**, such that the beam makes a second pass through the PA along a path that is substantially parallel to the

chamber axis, as shown in **Figure 7(d)**. Even without spatial filters in such an exemplary configuration, much less ASE is produced, such as a reduction on the order of at least a factor of 10, while maintaining about 50 mJ of the amplified output with 0.4 mJ in the input. One advantage of such a configuration is that the beam size substantially matches the gain volume cross section on the final pass and, therefore, the maximum output pulse energy can be obtained. In some variations of such a configuration, tilting of the beam path can occur, for example, in the plane of electrodes or perpendicular to such a plane. In some embodiments, both the first and second passes can be tilted relative to the chamber axis. The lens axes and slit of the second spatial filter can be oriented in the plane of electrodes or perpendicular to such a plane. Also, the beam does not have to be expanded on the second pass.

**Figure 8** shows another variation **700** on the configuration of Figures 6 and/or 7. In this layout, the coupling of the beam to the amplifier is accomplished using polarizers **702** and **704**. If the incoming beam is polarized in the plane of the Figure, for example, the beam can be transmitted through the first polarizer **702**, make a first pass through the PA **518**, and pass through a half-wave plate **704**. The half-wave plate will change the polarization of the beam to a perpendicular polarization coming out of the Figure, which will then reflect off the second polarizer **706** and be redirected to mirror **708**. The beam will pass through the second spatial filter **710**, containing lenses **712** and **716**, as well as slit **714**, be redirected by mirror **718**, and be reflected by the first polarizer **702**. After the beam makes a second pass through the amplifier, half-wave plate **704** will change the polarization of the beam back into the plane of the Figure, such that the beam will pass through the second polarizer **706** and function as an output beam. The placement of the waveplate **704** placed between polarizers **702** and **706** can ensure that the polarization of the beam changes from in-plane "p" to the orthogonal "s" on the first pass through the amplifier **518**, and from "s" to "p" on the second pass. Polarizers **702** and **706** can be highly transparent for a "p" polarized beam, guaranteeing that there are no oscillations in the apparent ring cavity formed by polarizers **702** and **706** and mirrors **708** and **718**, because in either direction the beam is transmitted completely outside the "cavity." One advantage of such a configuration is that the beam size can match the gain medium cross-section on both passes. A potential disadvantage to such an approach, however, is that polarizers in the UV range can be

expensive, can have relatively short lifetimes, and can have a low transmission and contrast ratio.

In the configurations of Figs. 6-8 described above, either the first or second spatial filter, or both, can be omitted from the system. Whether or not to include the spatial filters can depend, for example, upon the severity of the ASE problem. Again, an inherent advantage of a beam path such as those shown in Figs. 6-8 resides in the fact that the amplified beam does not propagate towards the oscillator, such that a major problem with feedback is resolved.

Further Variations

In certain embodiments, it can be advantageous to increase the output pulse length in order to, for example, reduce peak power in the optical components of the stepper. In order to increase the output pulse length, a layout similar to that shown in Figure 8 can be used, but with a polarizer that is partially transmitting for "s" polarization and highly transmitting for "p" polarization. Having a high transmittance for "p" polarization can ensure the absence of oscillations in the loop or ring path for the PA. Due to the partial transmission of "s" polarization, a portion of the pulse energy after the first pass can be coupled out and added to the second-pass output pulse. Since the latter pulse is delayed with respect to the former, the resulting output pulse can be elongated.

One advantage to such a configuration is the prevention of oscillations in the ring cavity by the complete outcoupling of the beam after the two passes. Using a partially reflective mirror in place of a pair of polarizers may not be satisfactory, however, as there might always be feedback in the ring cavity. A disadvantage is that the output can consist of two components polarized in the orthogonal planes. In such a case, a "polarization scrambler" can be used in order to create a randomly polarized output beam. Another possibility is to insert a quarter-wave waveplate in the output beam, such that the output beam can be circularly polarized.

In another variation, a layout similar to that shown in Figure 8 can be used, except that the first polarizer is replaced by a first partial reflector, the second polarizer is replaced by a second partial reflector, and the waveplate is removed. The product of the reflectivities of the first partial reflector and the second partial reflector must be small enough to not cause

oscillations in the ring cavity formed by the partial reflectors and reflecting mirrors. At the same time, the total transmittance through the path formed by the sequence of second partial reflector, second mirror, third mirror, and first partial reflector has to be sufficient to create usable input for the second pass through the amplifier. A fundamental assumption in this approach is that the pulse evolution from the noise level in the ring cavity takes longer than the arrival time of the pulse from the oscillator, such that the output consists primarily of the amplified main pulse and not ASE. Using this assumption, the feedback does not necessarily have to be below the oscillation threshold in the absence of the main beam from the oscillator. One potential disadvantage to such an approach is the potential for an increased level of ASE.

In another approach, systems such as that shown in **Figure 8**, and variations thereof as discussed above, can have the waveplate **704** placed between the first polarizer **702** and the discharge chamber **520**, instead of between the chamber **520** and second polarizer **706**. One advantage to such a configuration is that the intensity of radiation in the waveplate can be reduced. Brewster windows can be used to seal the chamber that are turned by 90 degrees, in order to minimize reflection losses on the second pass, which would be more "powerful" than the first pass.

Improved Amplification

Systems and methods in accordance with another embodiment of the present invention can provide improved amplification for an excimer laser using a MOPA configuration. A novel optical set-up can be used with the power amplifier in order to simultaneously achieve high amplification, low ASE, and extension of the temporal pulse. A follow-on optical pulse extension also can be used to reduce any unnecessary peak power.

An excimer laser in a MOPA configuration has the potential to meet the target performance requirements relating to the spectral purity and high average power necessary for micro-lithography applications. It is desired that such an excimer laser system deliver very high spectral purity, with low ASE background and a high average power of 40 W or more in order to support the throughput requirements of advanced lithography scanner systems. MOPA laser systems can generate a high pulse energy having high spectral purity. The optics in a scanner typical in lithography applications typically utilize fused silica as a

primary material, requiring the peak power of the laser pulses to be kept low in order to avoid the compaction of the material. This requirement presents a general conflict between the high power demand and the low peak power requirement of the pulsed excimer laser source. In order to meet the requirement of a high average power and low peak power, a long pulse length can be desirable.

Systems and methods in accordance with one embodiment of the present invention utilize a novel optical set-up which provides for the extraction of high energy levels from the amplifier having a long pulse length, allowing a laser pulse with low peak power to be extracted. A loop or ring structure of the optical configuration allows energy to be extracted from the amplifier independent from the oscillator pulse length. Such an approach avoids feedback that could interfere with the oscillator, and avoids optical surfaces that could cause the emission of ASE from the amplifier. Such an approach allows a long pulse to be extracted from the amplifier, while a standard pulse length can be used with the oscillator. Obtaining such a long pulse length from the amplifier does away with the need for a follow-on optical pulse extension of the output pulse. Such an approach can replace the classical approach used for the injection seeding of laser systems. In the classical approach, a cassegrain telescope-type approach is used for the amplifier, whereby the seed pulse enters through a hole in the rear HR mirror. The HR mirror and the resulting high ASE cause this approach to be less than desirable, in addition to the fact that this system does not allow the pulse to be extended by the delay time of the ring.

Optical pulse extenders have been developed in order to extend the output pulse after leaving the laser system, as described in US Patent No. 6,389,045 B1 incorporated herein by reference above.

**Figure 9** shows a configuration **800** creating a beam path that can be used in accordance with embodiments of the present invention, wherein a pulse extender is used as an integral part of the amplifier optics. In such a layout, the oscillator beam can be used to determine qualities of the laser beam, such as the wavelength, bandwidth, polarization, and direction. The first mirror **802** encountered by the beam coming from the MO can have a low reflectivity, such as on the order of 10% … 50%. The other mirrors **804, 808, 810** in the beam path can have a reflectivity close to 100% for the desired wavelength. The amplifier **812** schematically presents the amplification volume in the discharge chamber **814**,

which is pumped with timing corresponding to the oscillator beam. A beam-matching unit (BMU) **806** can be used, which represents optional optics that can be used to adapt the geometric beam size of the oscillator (not shown) to the amplifier **812**. The BMU **806** can incorporate a spatial filter to ensure that only high purity laser radiation enters the amplifier.

When reaching mirror **802**, a portion of the oscillator beam is directed towards the output **816** of the laser system. This portion of the beam can be used to probe, test, or monitor properties of the beam, such as by using another beam splitter to direct at least a portion of the beam to a diagnostic tool. The remaining portion of the oscillator beam can be steered via mirrors **804**, **808**, and **810** into the power amplifier **812**. In the BMU **806**, the beam can be adapted in size and/or spatially filtered. The oscillator beam can be amplified in the PA **812** if the oscillator and amplifier are properly timed. When reaching mirror **802**, a small portion of the amplified beam can be directed towards mirror **804**, and by way of mirrors **808** and **810** can re-enter the amplifier. The main portion of the beam passing through the amplifier can leave the laser system as output **816** through mirror **802**, which acts as an out-coupling mirror. The re-directed portion can undergo a second amplification via a second pass through the amplifier **812**, generating a second amplified pass which again splits off a portion at mirror **802** as output **816** and a portion that re-enters the amplifier **812**. In this configuration, the output pulse length is determined by the pulse length over which efficient inversion can be reached in the amplifier. A high energy can be extracted while maintaining a low peak power, providing the opportunity to optimize the amplifier to account for amplification characteristics. The distance between the mirrors of this layout can be varied, and the total length of the ring formed by the mirrors can be adjusted such that a continuous pulse with minimum peak power is achieved.

Such a layout maintains the polarization of the incoming oscillator beam. The BMU can be utilized to achieve a high spectral purity for the portion of the beam passing through the amplifier volume. The BMU can consist of a telescope-like device to adapt the beam shape, and a spatial filter to ensure high spectral purity. An advantage to such a configuration is that no optical surface is capable of reflecting light back into the oscillator, ensuring sufficient optical isolation between the MO and PA, and avoiding interference between the two beams. The low reflectivity of mirror **802** reduces the intensity of ASE which could enter the amplifier by way of mirror **802**.

The optics used in the BMU **806** can be arranged such that spatial filtering is achieved for light traveling in both directions. **Figure 10** shows a schematic of an exemplary BMU **806**, which consists of a two lens, positive branch telescope. A first aperture **902** is placed between the two lenses **900, 904**. The first aperture **902** can be used to block the high divergent ASE at the focus point between the lenses. A second aperture **906**, placed outside the lenses along the beam path, can be used to shape the beam in order to, for example, match the cross section of the amplifier volume. The timing of the amplifier can be adjusted such that the latter portion of the oscillator is used for amplification, whereas the start phase of the oscillator, which carries inferior spectral purity, does not receive amplification.

**Figure 11** shows another configuration in accordance with embodiments of the present invention. A ring structure is shown, which can have behind it the same motivation as with the ring structure of Figure 9. The layout of **Figure 11** is somewhat different, however, as another scheme is used for the injection seeding. In this layout **1000**, the oscillator beam enters the ring structure through an appropriately-shaped hole in mirror **1002** and finds amplification in the volume of the discharge chamber **1020** of the PA **1018**. A portion of the amplified beam is reflected by out-coupling mirror **1004**, as well as high reflectors **1006**, **1016**, and **1002**, back into the amplifier **1018**. Lenses **1008** and **1012** can be used to adapt the size of the beam to fill the complete cross section of the amplifier volume for the second pass through the PA **1018**. As described above, the lenses **1008, 1012** and apertures **1010, 1014** can be utilized for spatial filtering.

**Figure 12** shows another such system **1100** where the MO **1102** is again separated by a means of optical isolation **1104**, such as any of the optical isolation means described herein. In this layout, however, a pulse extender arrangement **1106** is inserted before the amplifier **1108** in order to reduced energy loss in the pulse extender. A pulse from the master oscillator **1102** will pass through the optional means of optical isolation, such as a spatial filter, and will be input to the pulse extender **1106**, also known as an optical delay line. The pulse extender can include any appropriate optical elements, such as a beamsplitter **1110** and highly reflective mirrors **1112** and **1114**. The beam splitter **1110** can reflect a portion of the incoming beam toward turning mirror **1116**, and a portion of the incoming beam toward the delay line formed by mirrors **1112** and **1114**. Upon the first round trip in the delay line **1106**, the delayed pulse can be partially transmitted through the beam splitter **1110** so that the

delayed beam overlaps spatially with the original partially reflected beam. The remaining portion of the delayed beam can be recirculated in the delay line. The delay line acts as a pulse extender, as all the output pulses of the delay line overlap spatially. This extended pulse can then be amplified in the amplifier **1108**. This approach allows the length of the output pulse of a MOPA system to be increased, which can be beneficial for extending the lifetime of the optics in the optical scanner.

Using a single-pass amplifier with the above approach can provide an unnecessary limitation. In order to properly amplify longer pulses, the amplifier may need to have an equally long pulse gain. In a typical laser, making the gain pulse longer requires compromising other important parameters, such as the pulse energy stability. A multi-pass amplifier can avoid such limitations.

As shown in the layout **1200** of **Figure 13**, the optical delay line **1204** essentially creates a sequence of two pulses of similar energy, followed by a series of much weaker pulses (not shown). The optimal reflectivity of the beam splitter **1208** used can be any appropriate value, such as for example approximately R = 38%. This two-pulse sequence can be treated effectively as a single pulse of increased duration. The delay between these pulse sequences, or pulse pairs, can be adjusted to correspond to the delay between consecutive passes in the amplifier **1206**, shown schematically in **Figure 13**. In order to appropriately adjust the pulses, each pulse can be present in the gain medium during the gain pulse. The pulses will both be present when a first pulse is present in the amplifier **1206** on a second pass, and a second pulse is present in the amplifier on a first pass. The output of such a system can then include the two amplified pulses. This approach differs from certain embodiments discussed above, in that the pulse extender is positioned between the oscillator and amplifier stages. Since the pulse extender always transmits only a percentage of the incoming pulse, the pulse extender consumes much less energy, in absolute terms, when positioned before the amplifier rather than following the amplifier along the beam path.

It should be recognized that a number of variations of the above-identified embodiments will be obvious to one of ordinary skill in the art in view of the foregoing description. Accordingly, the invention is not to be limited by those specific embodiments and methods of the present invention shown and described herein. Rather, the scope of the invention is to be defined by the following claims and their equivalents.